Original Articles

Climate change impacts on the aptitude area of forest species

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ABSTRACT

Climate change has been most evident since the mid-twentieth century and has caused unprecedented planetary change. Economically, the agricultural sector may be the most affected by climate change, as agricultural and forest species are highly dependent on weather conditions. Given the background, the aim of this study was to assess the potential impact of climate changes on the delimitation of areas suitable for cultivation of the forest species *Azadirachta indica* (neem), *Bactris gasipaes* (pupunha), *Pinus caribaea* var. *hondurensis*, *Pinus elliottii* var. *elliottii*, *Pinus oocarpa*, *Pinus taeda, Tectona grandis* (teak) and *Toona ciliata* (cedar) in the Espírito Santo state, Brazil. For characterization of current climate, we used data from 1982 to 2011. The Global Circulation Model (MCG) and MRI-CGCM2.3.2 were used, respectively, to estimate mean annual precipitation and average air temperature for 2050. The projections generated point to reduction in monthly rainfall and increase in average air temperature by 2.1 °C. The annual water deficit will thus tend to increase in most regions within the state. Current and future agro-climatic zoning were compared using a paired comparison matrix. In future, all eight forest species will experience a reduction in suitable cultivation area, with teak likely to suffer least impact and cedar and pupunha likely to experience most widespread changes. Cedar, neem, pupunha, *Pinus caribaea* and teak will experience the highest percentages of exchange between classes, indicating the emergence of new areas suitable for cultivation under projected future climate conditions. The methodology can be adjusted to agricultural and forestry crops of other countries.

1. Introduction

Climate change has been most evident since the mid-twentieth century and has caused unprecedented planetary change. Studies show an increase in temperature of the atmosphere and oceans, a reduction in the amount of snow and ice, and rising sea levels and greenhouse gas concentrations (Dai, 2012; Fu et al., 2015; IPCC, 2007; IPCC, 2013; Peters et al., 2012; Rogelj et al., 2011; Romps et al., 2014; Trenberth et al., 2013). These changes can significantly affect living beings, as well as influencing various economic sectors (Peters et al., 2012).

The agricultural and forest species have their index of productivity directly correlated with the climatic conditions to which they are submitted (Assad et al., 2004; Campos et al., 2010). Thus, changes in the climatic conditions considered optimal for the development of a certain species generate losses of productivity and consequently economic losses (Andrade et al., 2012; Assad et al., 2004; Campos et al., 2010;

Ghini et al., 2007; Kosaka and Xie, 2013; Pezzopane et al., 2012; Rodrigues et al., 2005). In this sense, the meteorological elements affect not only the metabolic processes of plants, directly related to crop production, but also various field activities.

Numerous researchers have documented the impact of climate change on agro-climatic zoning (Andrade et al., 2012; Assad et al., 2013, 2004; Campos et al., 2010; Oliveira and Cecílio, 2011; Pezzopane et al., 2012; Silva et al., 2013), impacts on development and physiology (Broadmeadow and Ray, 2000), impacts on and environment (Eugenio et al., 2016a; Eugenio et al., 2016b; Santos et al., 2016), susceptibility to disease (Dukes et al., 2005; Ghini et al., 2007; Tubby and Webber, 2010), productivity of major forest crops (Baesso et al., 2010; Zhang et al., 2015), and impacts on the market and sustainable supply of wood for processing (Santos et al., 2017; Zhang et al., 2015).

Based on the studies cited above, it is very important to choose aptitude areas for the cultivation of each forest species according to their agroclimatic aptitude (Zhang et al., 2015). The state of Espírito Santo currently has agroclimatic and topographic conditions that favor the cultivation of different forest species (Oliveira et al., 2006). In order to the current index of forest productivity in the state do not decline, it is of fundamental importance to plan the possible impacts that climate change will have on the sector and to identify the areas that will be most apt in the future for the production of certain species.

However, it is clear that a purely quantitative assessment of percentage change in one area does not provide enough information to guide the planning and direction of public policies, based on an interpretation of the zoning of affected areas. Analysis of the timeline of change between aptitude classes of species is therefore an important advantage of this work on agro-climatic zoning.

The aim of this study was to assess the potential impact of climate changes on the delimitation of aptitude areas for cultivation of the forest species that have aroused interest in the rural producers of the state of Espírito Santo, Brazil: *Tectona grandis* (teak), *Toona ciliata* (cedar), *Azadirachta indica* (nim), *Bactris gasipaes* (pupunha). The delimitation of aptitude areas for cultivation was also carried out for four species of the genus Pinus ssp in Espírito Santo, Brazil. The four species of the genus *Pinus* spp were: *Pinus elliottii* var. *elliottii*, *Pinus caribaea* var. *hondurensis*, *Pinus oocarpa* and *Pinus taeda*. These species have been planted on a commercial scale in Brazil for more than 30 years, making them economically viable due to their great versatility in growing and producing wood in the most varied types of environment, as well as the multiplicity of the use of its wood, enabling the generation of this natural resource throughout the national territory, replacing the native wood species (Paludzyszyn Filho et al., 2006).

2. Material and methods

2.1. Study area

The Espírito Santo state is located in the southeast of Brazil, delimited by the Atlantic Ocean to the East, Bahia to the North, Minas Gerais to the West, and the state of Rio de Janeiro to the South. It has a total area of 46,184 km^2 and lies geographically between the meridians 39° 38′ and 41° 50′ West and between the parallels 17° 52′ and 21° 19′ South. It is divided into 78 municipalities, with three major regions of relief (coastal areas, trays, and elevated areas of the interior) that determine, along with other factors, the diversity of state land (Fig. 1). It features flat and undulating areas, with climate influenced markedly by changes in altitude. As per the Köppen classification system, the region forms part of the humid climatic zones A and C. Climatic subtypes are Aw, Am, Cf, and Cw, as well as variations Cfa, Cfb, Cwa, and Cwb.

The representative map of Köppen's climate classification for Espírito Santo state, Brazil is shown in Fig. 2. According to Alvares et al., 2013 the predominant climatic zones in the state of Espírito Santo are Aw (Tropical zone – with dry winter), Am (Tropical zone – with monsoon), Cfa (Oceanic climate, without dry season) and Cfb (Oceanic

climate, without dry season - with temperate summer) with percentage values of 53.69%, 13.96%, 14.92% and 10.47%, respectively.

2.2. Database

Meteorological data (precipitation and temperature) were obtained for two different periods: a) period 01 – representation of the current scenario (1982 – 2011) and b) period 02 – for the representation of the future scenario (1971 – 1999).

2.3. Zoning of current climate and future aptitude of forest species

This step consisted of two delimitations of agro-climatic zones in Espírito Santo state, one considering the current climate and the other climate projections for the year 2050 linked to the pessimistic scenario A2[1]. The A2 scenario was chosen because previous research results show that for comparisons between the base period and the future projections, the outflows of the HadAM3P model with A2 scenario can represent the characteristics of circulation, precipitation and temperature over South America, where the study area is located (Marengo et al. 2009).

For current zoning, we used the historical series of updated climate data for the period 1982–2011. Geostatistical models (Exponential, spherical, Gaussian, linear) were used for interpolation of monthly precipitation data, with best performance evaluated according to Castro et al. (2010a,b), with a 1-km sized cell. Spatial distribution of average air temperature was performed using regression equations and updated coefficients for this data series.

Monthly rainfall data and average air temperature were used for future zoning, with regionalization (downscaling) of the A2 scenario for 2050 to a resolution of 1 km. Due to the best performance (low bias value between the observed and simulated data and the lowest value of root mean square error - RMSE), the Global Circulation Model (MCG) and MRI-CGCM2.3.2 were used, respectively, to estimate mean annual precipitation and average air temperature for 2050.

2.4. Normal climatological water balance

Using spatialized air temperature and rainfall data for current and future climate scenarios via the method proposed by Thornthwaite and Mather (1955), we calculated the normal climatic water balance for each pixel on the map. We used a programming routine in MATLAB®, with input data being monthly temperature maps, monthly precipitation, and a map of available soil water capacity (CAD) for Espírito Santo state developed by Silva et al. (2013). Due to the complexity and high computational demand for the pixel-to-pixel processing of the normal climatic water balance, the methodological steps are demonstrated, step by step, on the site https://doi.org/10.15809/irriga. 2013v18n1p01.

2.5. Determination of agro-climatic aptitude of forest species

According to Pereira et al. (2002), aptitude class is the identification and division of productivity areas based on their production potential. In other words, aptitude classes are areas where heat and water needs are evaluated to identify the most and least suitable sites for implantation of a culture.

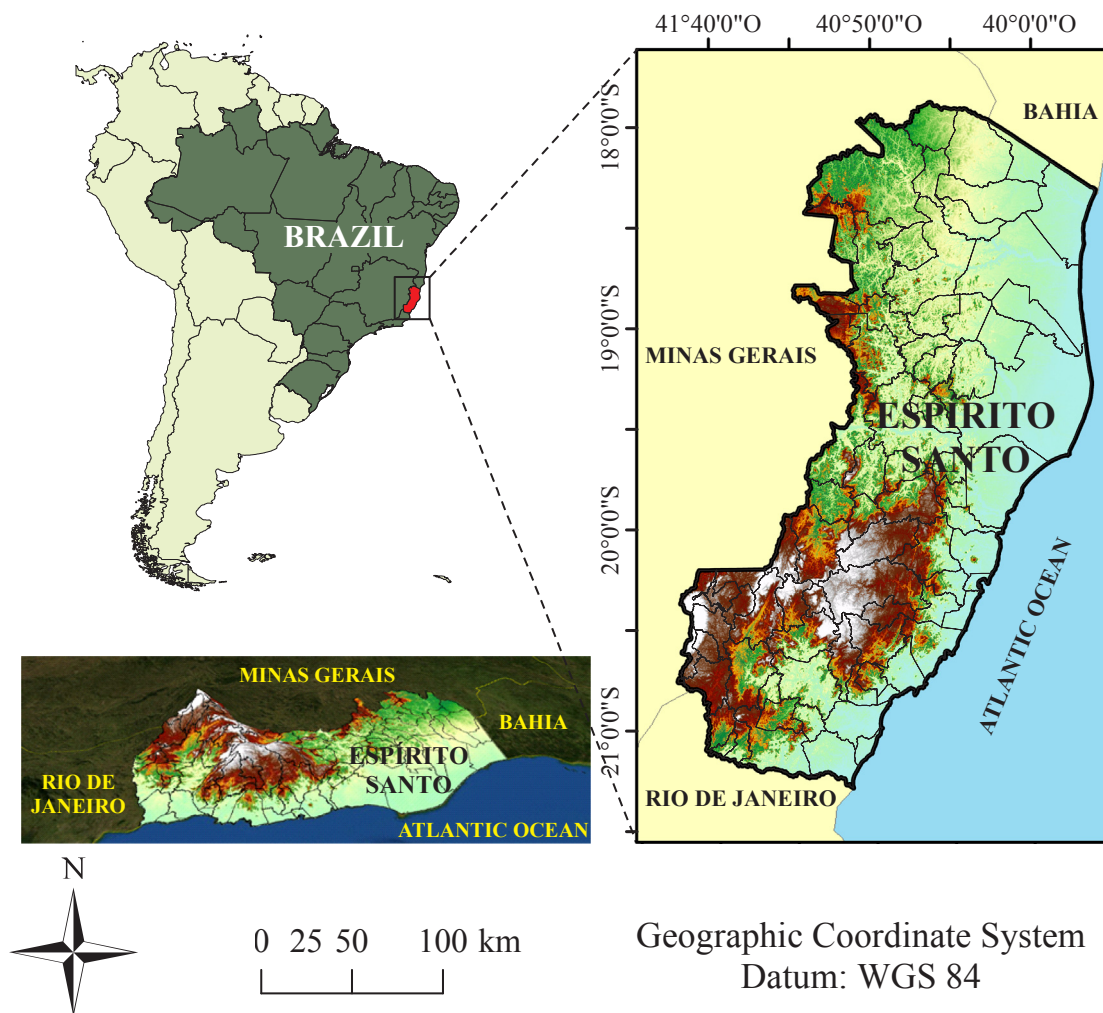In this study the forest species (*Azadirachta indica* (neem), *Bactris*

Fig. 1. Location of study area, Espírito Santo state, Brazil. Source: Santos et al. (2016).

gasipaes (pupunha), *Pinus caribaea* var. *hondurensis*, *Pinus elliottii* var. *elliottii*, *Pinus oocarpa*, *Pinus taeda*, *Tectona grandis* (teak) and *Toona ciliata* (cedar)) were classified according to their heat and water needs and divided into two climate aptitude classes (Table 1): Apt and Inapt, as follows: Apt: thermal and water conditions of the area are favorable for proper development and production of the species on a commercial scale, and Inapt: when normal climate characteristics are not suitable for economic exploitation of the species due to severe water and/or thermal limitations, with marked repercussions for production.

2.6. Agro-climatic zoning maps for forest species

Zonings were obtained through cross-tabulated maps that characterize thermal and hydrological conditions favorable for development of the studied species.

Once species were selected and climate indices were established, we used the computer application ArcGis 10.2 to perform and generate all mappings. The flowchart in Fig. 3 shows all required operations to achieve zoning for current and future climate, respectively.

2.7. Analysis of spatial fluctuations of aptitude class changes

After obtaining the final zoning outputs, we used the map overlay technique, using current and future zoning, to generate a new map indicating changes in aptitude classes occurring over this time interval and showing net change (including gains, losses, and persistence for each agro-climatic aptitude class of each forest species).

To quantitatively analyze the changes taking place, a pairwise comparison matrix was applied, according to the methodology proposed by Pontius et al. (2004). We identified spatial changes in aptitude classes of each species by calculating transitions between apt and inapt areas. To construct the matrix (Table 2), we compiled overall proportions of classes (current data) in rows and (future data) in columns, in order to compare them; analysis of the comparison then enabled the detection of transitions between classes.

The "gain" represented in the row of the matrix corresponds to total increases for a given class between current and future dates, calculated as the difference between the total of the class under a future climate and the persistence of this class. The "loss" represented in the matrix column represents the total losses related to a given class between current and future dates, calculated as the difference between the total percentage area of the class under current climate and the area of persistence of this class.

The parameter "net change" was calculated according to Eq. (1), to measure the level of change, based on the percentage of each class:

$$\text{Netchange} = |\%C_{j1} - \%C_{j2}| \tag{1}$$

where $\%C_{j1}$ is class j percentage of zoning for the current climate and $\%C_{j2}$ is class j percentage of zoning for future climate.

The parameter "exchange" (swap) was calculated according to Eq. (2) and represents the total area of a class lost in one location but offset by a gain in area of the same class in another location, and vice versa. Pontius et al. (2004) defines this as double the minimum percentage of gain or loss for a given class.
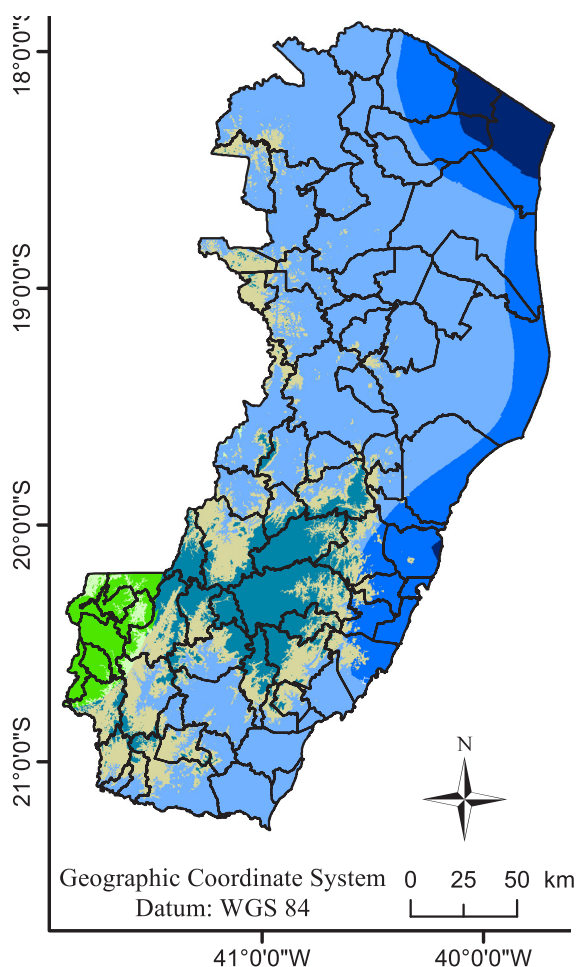
Fig. 2. Köppen's climate classification for Espírito Santo state, Brazil. Adapted from Alvares et al. (2013).

$$S_j = 2. \, \min(\text{gain, loss}) \tag{2}$$

3. Results

The coefficients of the regression equations for estimating the monthly and annual values of mean air temperature for the current period, with their respective adjusted coefficients of determination (R2) for Espírito Santo state are show Table 3.

The values of the coefficient of determination (R2) show small variation between the months of the year, allowing to verify the level of fit of the data to the equation obtained. The highest value of R^2 is 0.97 for the month of March, while the lowest R^2 found is 0.92 for the months of June and July and 0.96 for the months of November, December and average annual temperature.

In the average temperature equations for the current period, the longitude is not significant for the months of May to July, as well as for the latitude variable, in which besides these months, it also did not present significant interaction for the months of January and February.

Table 4 shows changes in the area suitable for cultivation of forest species in the Espírito Santo state, based on a comparison of current and future climate, the latter based on the pessimistic A2 scenario of IPCC models for 2050.

As a result of climate change, all eight evaluated forest species will suffer reduction in areas suitable for their cultivation in Espírito Santo state. *Tectona grandis* (Teak) is the species that will experience least impact, with a reduction of 2.1% in suitable area.

Under current climate conditions, *Bactris gasipaes* (pupunha) and *Toona ciliata* (cedar) are the species with the highest percentage of suitable area for cultivation in the state; however, these are also the species that will suffer the greatest change, with suitable area reduction of 34.23% and 30.8% by 2050, respectively.

Of evaluated species of the genus *Pinus*, *Pinus caribaea* var. *hondurensis* will suffer the greatest loss of suitable area (−20.8%); however, due to its ability to grow at higher temperatures compared to other *Pinus* species, it retains more growing aptitude across the state.

Fig. 4 shows the percentage of return and net change of agro-climatic aptitude classes of the eight evaluated forest species. These results were processed based on the methodology proposed in Table 2 and Eqs. (1) and (2).

The map in Fig. 5 shows spatial change in agro-climatic aptitude classes of *Tectona grandis*, *Bactris gasipaes*, *Azadirachta indica* and *Toona ciliata* in Espírito Santo state between the current period and the year 2050.

In terms of future projections, all species exhibit coastal migration trends to mountainous regions in an attempt to meet their climatological requirements.

Areas suitable for cultivation of *Tectona grandis*, both presently and in future, are mainly areas where water stress is < 100 mm per year and where average annual temperature > 22 °C.

There are areas suitable for cultivation of Indian Neem in parts of the south, the littoral, and the north, under both present and future conditions.

Currently, most of the area of study has climatic conditions favorable for development of commercial scale cedar. With climate change, much of the apt area of this species will be lost in the north as a result of increased water deficit in this region to > 400 mm.

Fig. 6 shows spatial fluctuations in agro-climatic aptitude classes for *Pinus elliottii* var. *elliottii*, *Pinus caribaea* var. *hondurensis*, *Pinus oocarpa* and *Pinus taeda* in Espírito Santo state between the present and the year 2050.

Potential areas for *Pinus elliottii* cultivation are mainly concentrated in regions of milder temperature, where annual water deficit is < 50 mm. An increase in these climatic variables causes reduction in areas of agro-climatic aptitude for cultivation of this species.

Pinus caribaea var. *hondurensis* currently has suitable area across a range that extends from the south to the north-west region throughout the coast. This range could be restricted in future in areas with water deficit > 200 mm.

Pinus oocarpa requires maximum annual average temperature of 21 °C, combined with tolerance to water deficits < 200 mm per year; there is a predominance of areas meeting these conditions that are climatically apt for cultivation of the species, under both current and projected future climate conditions, in localities with mildest climate in regions of higher altitudes. With an increase in air temperature, a small

Table 1

Average annual temperature range (Ta) and average annual water deficit apt and inapt for the development of the forest species studied.

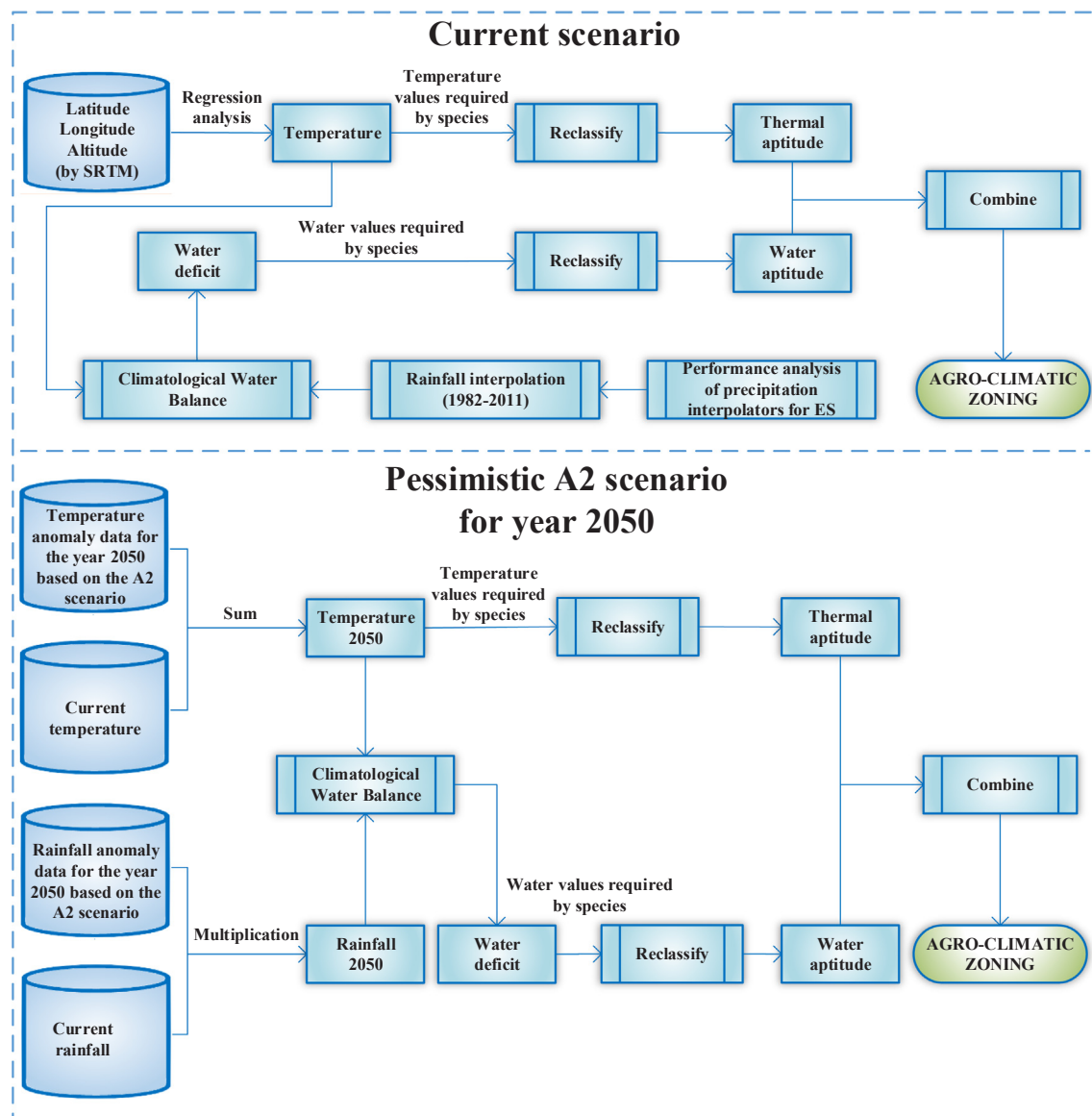| Culture	Regions				References
	Apt		Inapt		
	Temperature	Water deficit	Temperature	Water deficit	
Azadirachta indica (neem)	20 °C ≤ Ta	≤ 180 mm	20 °C > Ta	> 180 mm	Martins (2008), Neves and Carpanezzi (2009), Prates et al. (2005)
Bactris gasipaes (pupunha)	20 ≤ Ta ≤ 25 °C	≤ 350 mm	20 > Ta > 25 °C	> 350 mm	Bastos et al. (2008), Bovi (1998), Chaimsohn (2000), Neves et al. (2007)
Pinus caribaea var. hondurensis	21 ≤ Ta ≤ 27 °C	≤ 200 mm	21 > Ta > 27 °C	> 200 mm	Carpanezzi et al. (1986), Golfari (1975)
Pinus elliottii var. *elliottii*	15 ≤ Ta ≤ 24 °C	≤ 50 mm	15 > Ta > 24 °C	> 50 mm	
Pinus oocarpa	13 ≤ Ta ≤ 21 °C	≤ 200 mm	13 > Ta > 21 °C	> 200 mm	
Pinus taeda	13 ≤ Ta ≤ 19 °C	≤ 50 mm	13 > Ta > 19 °C	> 50 mm	
Tectona grandis (teak)	22 ≤ Ta ≤ 46 °C	≤ 100 mm	22 > Ta > 46 °C	> 100 mm	Araujo et al. (2012), Carvalho (1994), IPEF (2003), Nappo et al. (2005), Salazar and Albertin (1974)
Toona ciliata (cedar)	20 ≤ Ta ≤ 26 °C	≤ 400 mm	20 > Ta > 26 °C	> 400 mm	Carvalho (1994), Pinheiro et al. (2003), Ricken et al. (2011)

Fig. 3. Methodological steps used to obtain agro-climatic zoning of forest species in the Espírito Santo state, for the current climate and predicted climate conditions in the year 2050 based on the A2 scenario.

Table 2

Pairwise comparison matrix for two agro-climatic aptitude maps under two different sets of climatic conditions (current and future), showing the proportion of possible combinations of class changes.

Current	Apt	Inapt	Total	Loss
Future				
Apt	P_{AA}	P_{AI}	T_{1A}	$T_{1A} - P_{AA}$
Inapt	P_{IA}	P_{II}	T_{1I}	$T_{1I} - P_{II}$
Total	T_{2A}	T_{2I}		
Gain	$T_{2A} - P_{AA}$	$T_{2I} - P_{II}$		

PAI – proportion of area with transition from apt class (A) to inapt class (I); PIA = proportion of area with transition from inapt class (I) to apt class (A); PAA PII = areas that remained apt and inapt, respectively; T1 = total area of each class under current climate; and T2 = total area of each class under future climate. Adapted from Pontius et al. (2004).

Table 3

Coefficients of the regression equations for estimating the monthly and annual values of mean air temperature for the current period, with their respective adjusted coefficients of determination (R2) for Espírito Santo state.

Month	Coefficient ($\beta0$)	Altitude($\beta1$)	Latitude ($\beta2$)	Longitude ($\beta3$)	R2
JAN	−10.5297	−0.0067	ns*	−0.9406	0.93
FEV	−8.3819	−0.0070	ns*	−0.8999	0.92
MAR	−2.8703	−0.0068	0.4808	−0.9838	0.96
ABR	−2.3324	−0.0069	0.5545	−0.9729	0.95
MAI	24.4258	−0.0071	ns*	ns*	0.93
JUN	23.0662	−0.0074	ns*	ns*	0.92
JUL	22.6625	−0.0074	ns*	ns*	0.92
AGO	−26.1291	−0.0077	0.5904	−1.5007	0.95
SET	−29.9572	−0.0071	0.7029	−1.6677	0.95
OUT	−32.1183	−0.0068	0.8049	−1.8045	0.95
NOV	−21.9893	−0.0065	0.6559	−1.4980	0.96
DEZ	−11.3545	−0.0064	0.4716	−1.1688	0.96
ANUAL	−13.5899	−0.0070	0.5613	−1.2324	0.96

*Not significant at 5% probability level by Student's *t*-test ($p < 0.05$).

Table 4

Apt areas for growing forest species in the Espírito Santo state under current weather conditions and according to IPCC model data for 2050 for the A2 scenario.

Forest species	Current weather		Scenario future		Change	
	(1982–2011)		2050 (A2)			
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Azadirachta indica (neem)	19,923.1	43.24	12,258.0	26.6	−7,665.1	−16.6
Bactris gasipaes (pupunha)	39,424.3	85.56	23,650.3	51.33	−15,774.0	−34.2
Pinus caribaea var. *hondurensis*	23,000.4	49.92	13,396.7	29.07	−9,603.7	−20.8
Pinus elliottii var. *elliottii*	13,743.0	29.83	8,384.7	18.20	−5,358.3	−11.6
Pinus oocarpa	12,239.7	26.56	6,641.3	14.41	−5,598.5	−12.1
Pinus taeda	4,893.8	10.62	1,224.7	2.66	−3,669.0	−7.9
Tectona grandis (teak)	7,470.8	16.21	6,508.8	14.12	−961.9	−2.1
Toona ciliata (cedar)	40,565.5	88.04	26,374.4	57.24	−14,191.0	−30.8

area with average temperature < 13 °C will become suitable for cultivation of *Pinus oocarpa*.

Pinus taeda is a species with smaller extent of aptitude in the study area, due to it needing milder temperatures < 19 °C and its low tolerance to water stress, supporting a maximum annual deficiency of 50 mm.

4. Discussion

Heat is essential for the maintenance of plant life, but it must occur in a sufficient range and not excessive. Each metabolic process is adjusted within a temperature range – ranging from a little below 0 °C to a little over 40 °C, limiting the functionality of the enzymes – but optimum growth is only achieved if the various processes involved in metabolism and development are in harmony with each other (Chmura et al., 2011).

The increase in temperature increases the photorespiration since the O_2/CO_2 ratio is altered (Marengo, 2007), high temperatures also cause an increase in the evapotranspiration and evaporation processes (Taiz and Zeiger, 2008), thus altering the cellular metabolism and consequently of the plant as a whole.

Temperatures greater than those considered suitable for the species may cause problems for plant growth, inactivating or accelerating enzyme systems, promoting coagulation and denaturation of proteins, cytoplasmic disintegration and other biochemical disorders usually expressed as tissue injury (Agrios, 2005).

Climate change in Brazil threatens to intensify the difficulties of access to water, the combination of changes in climate elements, in the form of lack of rainfall or low rainfall accompanied by high temperatures and high rates of evaporation and, with competition for water resources, can lead to a potential crisis (Marengo, 2007), mainly for those producers, or in crops where irrigation is not feasible.

Tonello and Teixeira Filho (2012) point out the leaf water potential as one of the most important factors affecting the functioning of the stomata. In this way the water availability directly affects the gas exchanges. Evaluating 203-day-old eucalyptus seedlings, these authors verified that seedlings with lower water potentials showed lower transpiration rates indicating that the greater the restriction of water available in the soil to meet their physiological needs, the plant will exercise restrictions on the opening of its stomata to release water into the atmosphere, and thereby the absorption of CO_2.

The water availability altered the rates of eucalyptus photosynthesis in the study by Tatagiba et al. (2007), with a reduction of photosynthesis the longer the period of water restriction. Thus, the larger the water restriction, the lower the development and productivity of the forest species.

Of the forest species assessed, teak is the least affected by changes in agro-climatic zoning. Cotta (2010) found that, at present, 58.5% of the Espírito Santo state can support teak cultivation, with 41.5% of inapt area; in another estimate, Klippel et al. (2013) noted that 33.3% of land in Espírito Santo state is presently able to support teak cultivation. These results differ from those observed in this study due to differences in the methodology used for determing water balance. These two authors calculated water balance for each rainfall station (110 points) and not for each pixel and using a different period of data (1982 – 2011); furthermore, literature consulted in this study showed lower tolerance of teak to water deficit (100 mm) than the information used by these authors (150 mm).

It can be noted that the methodology adopted for spatialization of climate variables and for obtaining an updated database strongly influences the outcome of agro-climatic zoning, indicating the need for periodic updating of boundary information aptitude areas.

According to Figueiredo et al. (2005), teak forest species, although able to grow in areas with widely varying weather conditions, grow best in moderately humid and warm tropical conditions and require a biologically dry season of up to three months. Irrigation is needed if the annual water deficit > 100 mm.

Pupunha is among the species with the highest percentage of suitable land for cultivation in Espírito Santo state, with the exception only of areas of higher water stress. Bastos et al. (2008) note that in areas where there is a strong water restriction of four to five months, irrigation could possibly remedy this constraint to Pupunha cultivation; however, precautions should be taken to avoid economic and
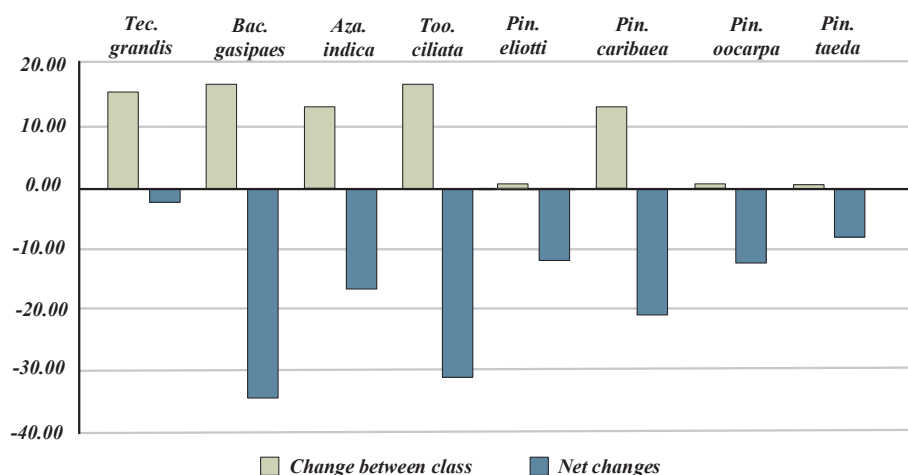
Fig. 4. Percentage of net change and exchange between agro-climatic aptitude classes of forest species in the state of Espirito Santo, between current conditions and predicted 2050 climate (as per A2 scenario).

environmental risks. Klippel et al. (2013) also noted this problem and reported that in such regions, the possibility of using irrigation should be studied so to allow cultivation of pupunha. It should be noted that, along with the cedar, the pupunha is among the forest species likely to suffer greatest impact from climate change, as evidenced by higher net change values.

Even though neem can potentially grow across almost half of the state's territory, intensified drought can lead to a reduction in planting areas. Increasing use of neem for various purposes brings with it a greater requirement for information on the cultivation of this species, including on its response to water stress situations. Martins (2008) found that under native vegetation conditions, drought reduced height, the number of leaves, and the stem diameter of neem.

According to Neves and Carpanezzi (2009), neem cultivation in Brazil extends across various climate types, from semi-arid to tropical rainy climates; this does not take into account additional influence of the natural environment or regional markets. Agro-climatic zoning of the kind conducted in this study is therefore important in order to select areas for better development of the species.

According to Klippel et al. (2013), neem is a forest crop that is well adapted to the climatic conditions found in Espírito Santo state. Projected changes in both temperature and precipitation may not necessarily restrict the extent of regions favorable for its cultivation in the state, as long as certain cultivation practices (such as use of irrigation) are adopted; this is because in future, species will be more constrained by water deficits above accepted values than by higher temperatures.

Most of Espírito Santo state is able to support cedar cultivation, but this species does not grow well only in the colder regions of the state. In a small-scale study of agroecological zoning in the basin of the Itapemirim River (ES), Paiva et al. (2007) also noted constraints on planting of this species at higher altitudes, located in the mountainous and Caparaó regions of the state. Remaining areas offer good conditions for cedar cultivation.

However, the cedar is one of the species expected to experience greatest impact of climate change, with considerable reduction in suitable agro-climatic area. A study assessing the global impacts of climate change and climate variability in forests and forest products indicates that climate change might affect the productivity of forests, with consequent impacts on the market and supply of wood for other uses, such as power generation with biomass (Perez-Garcia et al., 2002).

Apt planting area for *Pinus elliottii* is currently available in northern Espírito Santo, even if only in a small isolated spot. This result concurs with results of Oliveira and Cecílio (2011), who found that suitable areas for planting of *Pinus elliottii* var. *elliottii* cover much of the south, especially higher altitude areas where air temperature is lower and

annual water deficit is low or absent.

According to Castro et al. (2010a,b), *Pinus elliottii* var. *elliottii* is the species most suitable for planting in areas with altitudes > 500 m, where temperatures are milder.

In the work of Araujo et al. (2012) focused on the Federal District, the potential area for *P. elliottii* cultivation was found to be restricted by the combination of water deficit values (up to 200 mm/y), by precipitation (1400–1800 mm/y), and by climate (Aw – temperature average coldest month ≥ 18 °C and warmer months ≥ 22 °C).

With intensification of drought caused by climate change, by 2050 only part of the Serrana and south regions are expected to be suitable for planting of *Pinus elliottii*. These results differ from those of Oliveira and Cecílio (2011), who assessed the possible impacts of climate change on agro-climatic zoning of *Pinus elliottii* in the state of Espirito Santo, and concluded that 100% of the territory would be unfit for cultivation by 2050; however, the work of these authors relating to current and future water balance was based on HadCM3 and did not use downscaling techniques to regionalize data anomalies. Use of such GCM data on a regional scale requires caution.

Among species of its genus, *Pinus caribaea* is the one that has most agro-climatic aptitude for Espirito Santo and that will suffer least reduction in planting area as a result of climate change, being tolerant of higher temperatures. These results are in agreement with those of Oliveira and Cecílio (2011), who noted that this species can be grown almost along the entire coast and in some northern cities of Espirito Santo; this is not the case for *Pinus elliottii* var. *elliottii, Pinus oocarpa*, and *Pinus taeda*.

In a study of small-scale zoning in the Federal District, Araujo et al. (2012) found that *Pinus caribaea* species exhibited no restrictions related to altitude parameters, precipitation, and drought. The feature that most influenced the distribution of potential areas was weather.

The same was reported by Oliveira and Cecílio (2011), who noted that the impact of climate change on the behavior of this species was lower when compared to *Pinus elliottii* var. *elliottii*, due to its lower water requirement and consequent ability to tolerate precipitation reduction and temperature increase over the next decades. It is known that the Serrana region of the state is the one with greater extent of *Pinus* plantations with sawmills. Loss of suitable areas to other species of the genus (mainly *Pinus elliottii* and *oocarpa*) in this region as a result of climate change may be compensated for by replacing some planting areas with areas suitable for *Pinus caribaea*, so that the wood market for pine lumber in the state could continue to be fueled by this species that is more tolerant to heat.

The occurrence of events of this nature is mentioned by Campos (2011), who notes that positive temperature anomalies may contribute
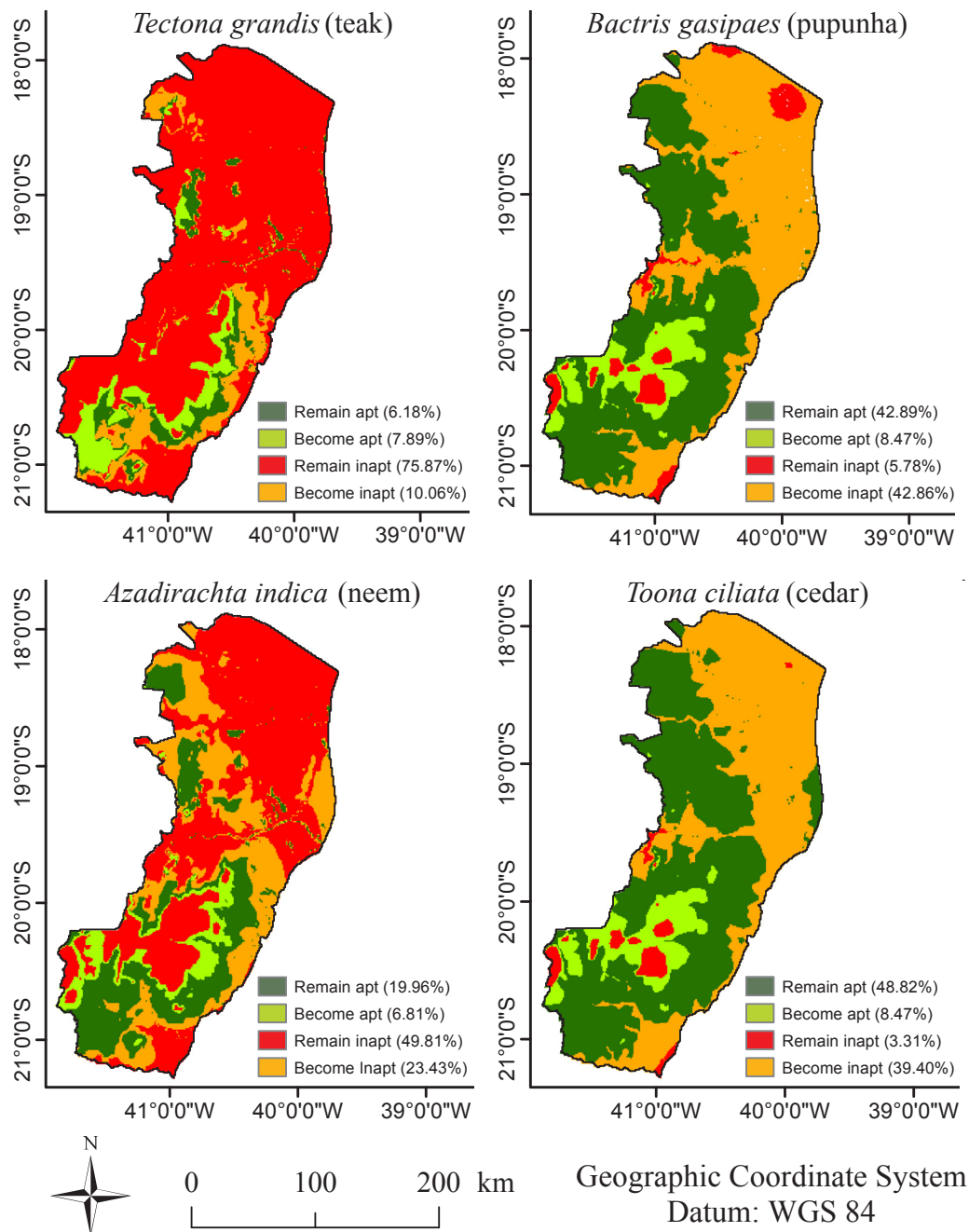
Fig. 5. Spatial change in agro-climatic aptitude classes of *Tectona grandis*, *Bactris gasipaes*, *Azadirachta indica* and *Toona ciliata* in Espírito Santo state between the current period and the year 2050.

to delimitation of cultivars suited to certain regions; the higher the anomaly, the closer the limit of biological tolerance to heat; however, other more heat-resistant crops can benefit.

There are potential areas for cultivation of *Pinus oocarpa* and *Pinus taeda* only in the colder regions of the state (south and Serrana); increased climate average air temperature changes will significantly reduce the extent of these areas. Similar observations were made by Castro et al. (2010a,b) and Oliveira and Cecílio (2011); using a historical series of meteorological data for the period 1977–2006, the authors concluded that these species can develop only in a small portion of the mountain region of Espírito Santo state with higher altitude and milder air temperature.

These results for current weather conditions are similar to those of Castro et al. (2010a,b), who emphasized that climatically suitable areas

for planting of *Pinus oocarpa* are more widespread in extent when compared to those suitable for *Pinus taeda*. The two species have very similar thermal requirements, but *Pinus oocarpa* can tolerate water stress up to 200 mm, while *Pinus taeda* can only tolerate up to 50 mm.

When comparing these four species of *Pinus*, it appears that the Espirito Santo state has a smaller area able to support *Pinus taeda* cultivation. Castro et al. (2010a,b) also observed that *Pinus caribaea* var. *hondurensis* has the largest agroclimatically suitable cultivation area and *Pinus taeda* has the least. The authors note that, as this species does not tolerate water deficiency > 50 mm, it is not suitable for planting in most of the state, as the water deficit is higher than this limit almost across all the territory.

Oliveira and Cecílio (2011) found that *Pinus taeda* would be the most affected by climate change, with apt areas in Espírito Santo state
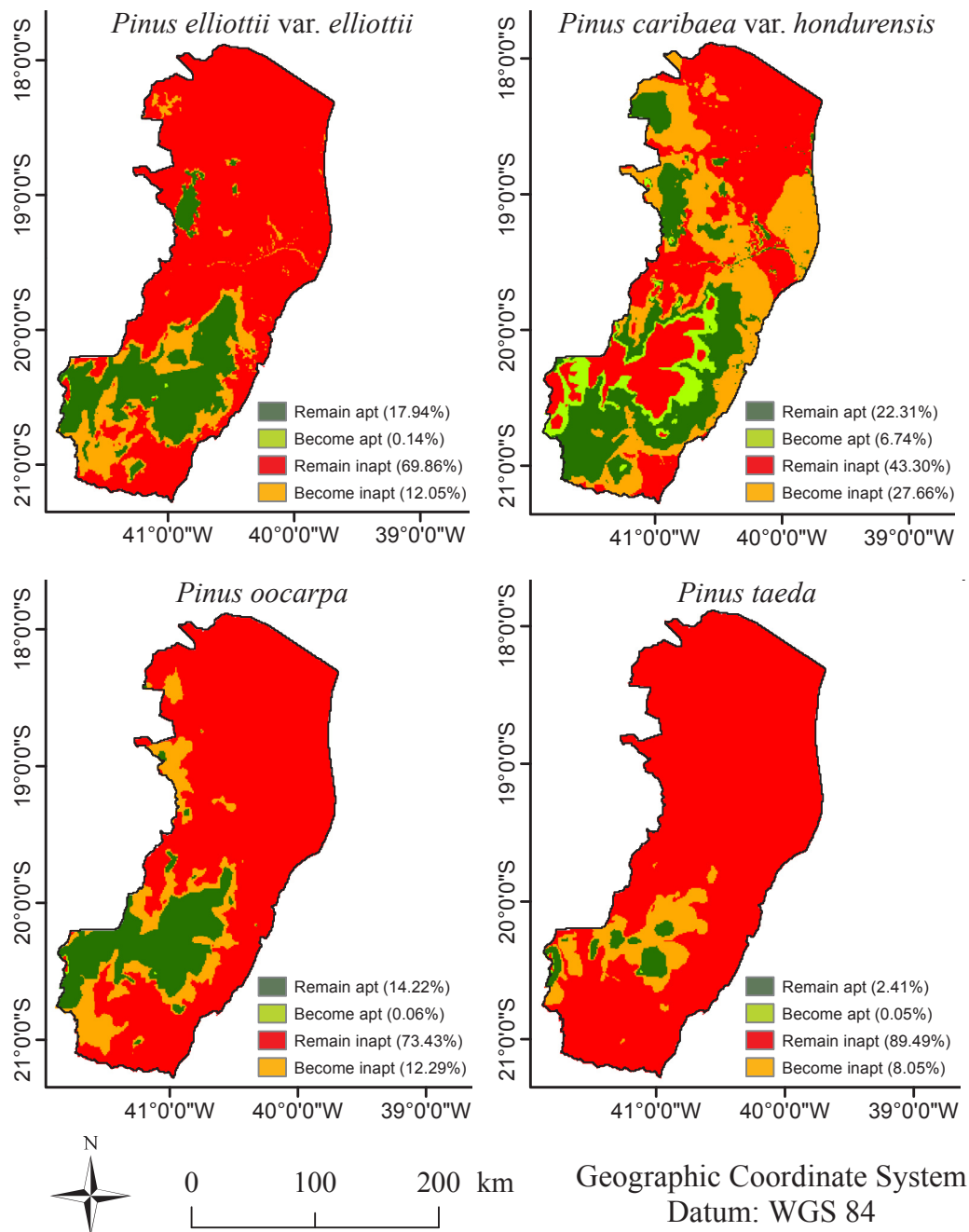
Fig. 6. Spatial fluctuations in agro-climatic aptitude classes of *Pinus elliottii* var. *elliottii, Pinus caribaea* var. *hondurensis, Pinus oocarpa* and *Pinus taeda* in the Espírito Santo state between the present and the year 2050.

disappearing completely by 2050 because of the restricted range of thermal aptitude and low tolerance to water stress. However, the authors considered only HadCM3 data, without using downcalling.

Of the species evaluated in this study, those likely to experience the largest net change in cultivation area with climate change in Espírito Santo state are pupunha and cedar; teak has the lowest value of variation in aptitude classes with changes in weather patterns. However, Pontius et al. (2004) point out that lack of net change does not necessarily indicate a lack of change between one date and another. It may be that the changes in suitable areas occur, but the amount or percentage of overall suitable area remains the same, for example, when loss of suitable area is accompanied by a gain of the same extent in another location. This constitutes "exchange" between classes.

Most of the species assessed in this study are expected to experience

considerable percentage of exchange between aptitude classes with climate change; in ascending order of value, these are pupunha, cedar, teak, *Pinus caribaea,* and neem. There is therefore the possibility that these species will be able to be cultivated in new planting areas. Manandhar et al. (2010) point out that an assessment of net change in isolation can lead to drastic underestimation of total change, since it cancels out gross gain in a category in a location with the same pre-tax loss in the same category at another location.

Several works are found in literature relating to landscape ecology and land use change analysis that use this method of analysis of spatial fluctuations between classes (Aldwaik and Pontius, 2012; Galante et al., 2009; Manandhar et al., 2010; Nagabhatla et al., 2012; Pérez-Hugalde et al., 2011; Pontius et al., 2004; Romero-Ruiz et al., 2012; Tavares et al., 2012), in order to detect changes over time; however, we have

not identified reports and studies assessing climate change, showing transitions between current and future classes, and analysing spatial fluctuations in classes generated by zoning.

Anthropogenic actions may affect the development of forest species, such as genetic structure, increasing inbreeding and genetic drift in fragmented populations (Montúfar et al., 2011).

A brief discussion on the current and future influence of climate on the adaptation of some species and their physiological development is described in the text below.

For *Bactris gasipaes*, when human intervention affects the environment, for example, temperature increases have the potential to extend palm trees distributions to higher environments and higher latitudes, but may negatively affect the individual carbon balance of these species. In the tropics, precipitation has a greater positive effect on palm trees wealth, where future changes in precipitation patterns may alter its distribution (Renninger and Phillips, 2016). Segundo estes autores, as palmeiras são uma das poucas monocotiledôneas que atingem alturas significativas com as mesmas restrições ambientais e fisiológicas que as árvores eudicotiledôneas, including long-distance water transport, and because they do not have vascular cambium, the constant addition of new conduits, depend exclusively on vascular bundles for the transport of fluids and mechanical stability.

In relation to *Tectona grandis*, Forest-Air-Carbon dioxide-Enrichment (FACE) studies predict that there could be a 23 to 28% increase in the productivity of these trees until 2050. However, the increase in global temperature can increase respiration by reducing the growth of these trees (Kallarackal and Roby, 2012).

For *Pinus taeda*, in water-limiting conditions there is an increase in the transcription of the gene encoding phenylalanine oxidase (PheH), where phenylalanine is a central amino acid in plants and precursor of many important secondary metabolites, such as lignin, phenylpropanoids and flavonoids (Frelin et al., 2017).

The explanations for the declines observed in the growth of Toona ciliata include water stress resulting from increased temperatures and El Niño events, increased respiration, changes in allocation or, more likely, a combination of these factors (Nock et al., 2011). According to Pumijumnong and Buajan (2013) the cambial activity measured by the counting of undifferentiated cell layers in the cambium zone from the anatomical microvessels of T. ciliata wood was higher during the transition from the dry season to the rainy season.

It should be noted that this study does not provide a definitive opinion regarding planting of these forest species, as silvicultural management practices, genetic improvement and the use of more heat resistant clones may enable the adoption of strategies that can circumvent the possible negative impacts of climate change on forest production.

5. Conclusion

Based on the conditions and methods adopted in the present study, the following conclusions were reached:

- By 2050, climate change (as projected by the A2 scenario of the selected model) will have an impact on suitable cultivation areas for the eight studied forest species.
- Analysis of the spatial variability of agro-climatic aptitude classes between current climate conditions and those projected for the year 2050 provides for better visualization of the results of agro-climatic zoning; this is a very important tool for forest producers, assisting in the planning of local planting and in the choice of species for planting.
- Teak is the species that is likely to experience lowest net change between apt and inapt areas, suffering only minor impacts of global climate change by 2050 in Espírito Santo state.
- Species likely to experience the highest net change between apt and inapt areas, suffering the greatest impact of global climate change

by 2050 in Espirito Santo state will be *Bactris gasipaes* and *Toona ciliata*.
- The proposed methodology can be adapted to other areas and agricultural crops.

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